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A Variable Asymmetry in the Circumstellar Disk of HH 30[1]

Karl R. Stapelfeldt[2], Alan M. Watson[3], John E. Krist[4], Christopher J. Burrows[4], David Crisp[2], Gilda E. Ballester[5], John T. Clarke[5], Robin W. Evans[2], John S. Gallagher III[6], Richard E. Griffiths[7], J. Jeff Hester[8], John G. Hoessel[6], Jon A. Holtzman[9], Jeremy R. Mould[10], Paul A. Scowen[8], and John T. Trauger[2]

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[1]Using the NASA/ESA Hubble Space Telescope

[2]MS 183-900 Jet Propulsion Laboratory, 4800 Oak Grove Drive Pasadena, CA 91109

[3]Instituto de Astronomía, Universidad Nacional Autónoma de México, J.J. Tablada 1006, 58090 Morelia, Michoacán, Mexico

[4]Space Telescope Science Institute, Baltimore, MD 21218

[5]Department of Atmospheric, Oceanic, and Space Sciences, University of Michigan, 2455 Hayward, Ann Arbor, MI 48109

[6]Department of Astronomy, University of Wisconsin, 475 N. Charter St., Madison, WI 53706

[7]Department of Physics, Carnegie-Mellon University, Wean Hall, 5000 Forbes Ave., Pittsburgh, PA 15213

[8]Department of Physics and Astronomy, Arizona State University, Tyler Mall, Tempe, AZ 85287

[9]Department of Astronomy, New Mexico State University, Box 30001, Dept. 4500, Las Cruces, NM 88003

[10]Mt. Stromlo and Siding Springs Observatories, Australian National University, Weston Creek Post Office, ACT 2611, Australia

ABSTRACT

We report Hubble Space Telescope observations of variability within the reflection nebulosity of HH 30, a compact bipolar nebula which is a nearly edge-on accretion disk system. A dramatic lateral asymmetry appeared in the upper reflection nebula in the spring of 1998, but was largely absent in 1994 and 1995 images. The variability timescale is much shorter than disk dynamical timescales at the projected radius of the asymmetry, which indicates that its origin is a variable illumination pattern projected onto the outer disk by changes in the inner disk or the central star. Orbital motion of coherent clumps or voids in the inner disk at radii of a few AU might produce such an effect. Another possibility recently proposed is accretion hotspots near the star's magnetic poles which produce broad beams of light sweeping across the disk as the star rotates. Simulated images of a disk illuminated by such a central "lighthouse" are a reasonable match to the bright lateral asymmetry in the upper nebula of HH 30. However, a model with identical opposed hot spots is excluded by the absence of a prominent asymmetry in the lower reflection nebula. Further temporal monitoring of the system is needed to better characterize the nebular variability and establish its physical origin.

1. Introduction

Accretion disks are found in a variety of astrophysical settings, from interacting binaries to active galactic nuclei. The best-resolved accretion disks are associated with young stellar objects (YSOs) in nearby star-forming clouds such as Taurus-Auriga. A prime example is Herbig-Haro 30, a young low-mass star in the L1551 molecular cloud which drives highly collimated bipolar jets (Mundt *et al.* 1990). Hubble Space Telescope (HST) observations of HH 30 (Burrows *et al.* 1996; Ray *et al.* 1996) have resolved this object as a compact bipolar nebula without a directly visible star. A dust lane, 450 AU in diameter, extends perpendicular to the jets and divides the reflection nebulosity into two lobes. Scattered light models (Burrows *et al.* 1996; Wood *et al.* 1998) have shown that the reflection nebulosities are most likely the illuminated upper and lower surfaces of a flared, optically thick, and nearly edge-on circumstellar disk which obscures the central star. With a linear resolution of 14 AU, the HST images of HH 30 allowed the first direct determination of the vertical scale height in an accretion disk. A growing number of edge-on YSO disks are being discovered with HST (McCaughrean *et al.* 1998; Krist *et al.* 1998; Stapelfeldt *et al.* 1998); their detailed study offers new opportunities to test theories of disk structure and evolution. This *Letter* reports on suprising changes within the reflection nebulosity of HH 30 which were discovered in parallel with monitoring of an expanding emission bubble in the nearby XZ Tauri system (Krist *et al.* 1999).

2. Observations and Results

We report on observations of HH 30 taken at three epochs with WFPC2 on the HST: a single 120 s exposure taken in 1994; a pair of 400 s exposures taken in 1995; and a new pair of 1100 s exposures taken in 1998. All exposures were taken in the F675W filter, which is roughly equivalent to Kron-Cousins R and includes many strong HH object emission lines. In all of the exposures HH 30 was placed on the WF2 camera which has a scale of about $0''\!.1$ per pixel. The exposures were reduced and calibrated following Holtzman *et al.* (1995a, 1995b), and the pairs of exposures were combined with positive outliers being rejected to eliminate cosmic ray events.

R band images of HH 30 at the three epochs are shown in the upper panels of Figure 1. The bright jet, faint counterjet, and reflection nebulosities flanking the edge-on disk are clearly seen at each epoch. The 1994 and 1995 images are similar, but a large lateral asymmetry has appeared on right side of the bright (upper or NE) reflection nebula in the 1998 image. A similar but much weaker asymmetry in this part of the nebula was noted in the 1995 images by Burrows *et al.* (1996). In 1998 the asymmetry is so prominent that the nebula center now appears displaced from the jet axis. The calibrated difference image between the 1998 and 1995 data clearly shows a brightening of the right (NW) side and a fading of the left (SE) side of the upper nebula. The peak of the bright asymmetry is located at a projected distance of $0''\!.7$ (100 AU) from the illuminating star. It covers a large portion of the right (NW) side of the upper nebula, with an area of about 0.27 arcsec^2 inside the half-maximum contour.

To quantify the changes in the reflection nebulosity, F675W magnitudes were measured for the left (SE) and right (NW) sides of the bright (upper) disk nebula (see Table 1). $1''\!.4 \times 1''\!.0$ apertures were used on each side of the jet; these encompassed the full radial extent of the nebula but were separated by a central $0''\!.3$ gap to avoid heavy contamination by jet emission. In the 1994 and 1995 data, there were only small lateral brightness differences in the upper nebula. The overall brightness of HH 30 declined between these two epochs, while the brightest side of the upper nebula reversed from the left to the right. In the 1998 data, the right side of the upper nebula becomes brighter, and the left side fainter, than at either of the two previous epochs. The resulting lateral asymmetry corresponds to about a factor of four in integrated brightness between the two sides of the disk.

Despite the large changes going on in the upper nebula, there has been little or no change in the brightness distribution within the fainter (lower) reflection nebula. The lower nebula appears somewhat brighter overall in 1998 than in 1995, but specific measurements are difficult to make from an F675W image alone because of jet contamination. The jet knots show further evidence for outward proper motions as described by Burrows *et al.* (1996); we will report on this in a future paper.

Table 1: F675W magnitudes of the bright (upper or NE) nebula

Epoch	left (SE)	right (NW)
05 Feb 1994	18.6	18.7
05 Jan 1995	19.2	19.1
25 Mar 1998	19.8	18.3

3. The Nature of the Asymmetry

The first issue to consider is the spectral character of the light comprising the variable asymmetry. A 1998 image is available in the F675W filter only, and includes significant contributions from both Herbig-Haro emission lines and reflected continuum light. However, images in a diverse set of filters are available from 1995 when a weak lateral asymmetry was present (Burrows et al. 1996, Ray et al. 1996). At this epoch, the asymmetry is clearly seen in broadband filters (F547M, F814W) that exclude bright emission lines. From this we conclude that a major fraction of the variable asymmetry is continuum reflected light. The asymmetry may also include an emission line component, but its strength is difficult to quantify because of uncertainties in continuum subtraction of the 1995 emission line images.

The key to understanding the origin of the asymmetry is knowing the timescale of its variability. The three epochs of HST R band images provide the only homogeneous dataset available with which to characterize the phenomenon, and they suggest a characteristic timescale of three years or less. However, if we adopt the conclusion that the asymmetry is present in continuum reflected light, we can make use of continuum measurements at other wavelengths to constrain the variability timescale. Near-infrared images in broad-band filters were made of HH 30 with HST/NICMOS on 29 September 1997 (program 7228), only 6 months before our WFPC2 image of 1998. These images show a bipolar nebula structure similar to that of the WFPC2 images, but with a lateral asymmetry opposite in polarity – the left (SE) side of upper nebula appears brighter than the right (NW) side – and of lesser amplitude (E. Young, personal communication). This suggests that the variability timescale is six months or less. However, this comparison must be interpreted cautiously due to the different column densities being probed at near-IR wavelengths.

Evidence for a long-lived or recurrent asymmetry is provided by an optical polarization measurement of HH 30 made by Cohen & Schmidt (1981). Their 1979 observations show a net continuum polarization of 2.8% at PA 93°. Simple symmetry arguments and detailed scattered light models (Whitney and Hartmann 1992) suggest that an axisymmetric edge-on disk should show a net polarization vector perpendicular to the disk plane: in the case of HH 30, at a PA of 32°. The significant difference between the observed and predicted polarization PAs is consistent with a large continuum scattered light asymmetry in 1979, and also suggests that regular polarization measurements could be used to monitor the asymmetry in lieu of subarcsecond images.

4. Mechanisms for the Asymmetry

It is clear that orbital or infall timescales for material near $r = 100$ AU are much too long to explain the variability which is seen. For the estimated central mass of 0.5-1.0 $M_{\odot}$ (Burrows *et al.* 1996), the dynamical timescale at this radius is many hundreds of years. The sound crossing time for the disk at this radius is larger still. Thus the motion of disk material or possible companion objects at the location of the asymmetry cannot account for the observed timescale. To verify this expectation, we examined the images to see if the vertical structure of the disk reflection nebulosity had undergone any change between 1995 and 1998. Brightness profiles were extracted in the region including the asymmetry, and are compared in Fig. 2. When normalized to the same peak brightness, there is no significant difference in the vertical profile of the nebula (and hence in the disk's vertical structure) between the two epochs.

A reflecting dust cloud moving out above the disk plane could produce the bright nebular asymmetry on the required timescale of a few years. The velocity of such a cloud would have to be at least 150 km s^{-1} to reach the radial extent seen; this is comparable to flow velocity measured for the emission line jets. An optically thin cloud with a mass just a few percent of $M_{\oplus}$ would be enough to produce the observed brightening, and would imply mass flow rates comparable in magnitude to those observed for the emission line jets (Mundt *et al.* 1990). It seems unlikely, however, that a cloud ejected above the disk plane could appear without affecting the nebula's vertical profile, which we have shown is unchanged. While a moving cloud might explain the brightening of the right (NW) side of the upper nebula, it cannot readily account for the simultaneous fading seen on its left (SE) side or the reversed asymmetry suggested by the NICMOS images. Thus we discount an outflow origin for the variable asymmetry.

Our working hypothesis for the variable asymmetry is that the outer disk acts as a screen upon which moving illumination patterns from the central object are projected. Enhanced illumination (a"beam") directed in the plane of the sky then would lead to lateral asymmetries in the disk reflection nebulosity, as seen in 1998. When directed toward or away from the observer, such a beam would produce a centrosymmetric nebula which mimics the uniformly illuminated case, as seen in 1994 and 1995. We now consider two possible mechanisms which could produce these effects.

4.1. Asymmetric propagation of starlight through the disk

The first mechanism posulates a clumpy inner disk at radii where the orbital timescales matches that of the observed variability. Dense clumps in this region would cast shadows on the outer disk, while voids would allow shafts of light to propagate outwards. This general picture has been offered to account for the variable reflection nebulosity seen on much larger scales in young stellar objects such as R Monoceros (NGC 2261, "Hubble's Variable Nebula"; Lightfoot 1989), PV Cephei (Cohen *et al.* 1981), and R Corona Australis (Graham and Phillips 1987). However, HH 30 would be the first such case where illumination patterns are observed within the disk itself. (There may be other examples: a subtle lateral asymmetry is present in the HK Tau/c disk, and we have seen variable structure in the compact bipolar nebula of DG Tau B). If a single inhomogeneity was responsible for the for the asymmetries seen in HH 30 from 1979-1998, then a mechanism would be required to maintain its coherence against Keplerian shear over many orbital timescales. Bar or spiral density wave structures in the inner disk, perhaps forced by a close companion, could satisfy this requirement, and are good candidates for beaming/shadowing the outer disk if their vertical expression extends to a few scale heights. Alternatively, individual clumps may be transitory but are replaced by the formation of new ones. Turbulence in the disk, especially if it takes place near the radial sublimation boundary for ices in dust grain mantles, might produce substantial azumithal variations in the extinction optical depth toward the outer disk. The radius for ice sublimation is likely to be a few AU, comparable to the radius inferred from the variability timescale. Thus a clumpy inner disk appears a viable model to account for the observations.

4.2. Intrinsically asymmetric illumination

A second mechanism has been suggested as a natural consequence of the accretion process itself. In a highly prescient paper, Wood & Whitney (1998; hereafter WW) proposed that the variability and small asymmetries in the 1994 and 1995 HST images of HH 30 might be explained by "hot spots" on the surface of the star, if those spots are asymmetrically distributed about the stellar rotation axis. Such hot spots are to be expected if stellar accretion occurs primarily along magnetic field lines onto auroral zones, rather than through a boundary layer at the stellar equator. If the magnetic poles are tilted significantly from the rotational poles, the body of the star will block these hot spots from view for half of the disk, producing an illumination pattern which moves across the disk as the star rotates.

To compare our new observations to this model, we used the Monte Carlo radiation transfer code employed by Burrows et al. 1996. Our code has evolved since its initial use to model HH 30, and now uses an improved integration scheme and a variant of the "forced escape" method of Henney & Axon (1995). We began by reproducing the model suggested by WW. For the disk, we selected model C2 from Burrows et al. (1996), but took $r_\star = 2\ R_\odot$ and $r_{\rm min} = 6\ R_\odot$ from Wood et al. (1998). The exponent in the scale height of the disk $\beta = 1.25$, which is in agreement with the predictions of Miyake & Nakagawa (1995) and D'Alessio et al. (1998) for an optically-thick flared disk in which gas and dust are well mixed. The disk is observed from a latitude of 8°. We took parameters for the star and hot spots from WW, that is, the hot spots have radii of 20°, latitudes of ±65°, and the star and hot spots emit as black bodies with temperatures of 3800 K and 10,000 K respectively. Each hot spot is about as luminous as the star in the F675W filter. The accretion rate implied by these assumptions (determined by equating the hot spot luminosity to the gravitational potential energy drop over the last few stellar radii) is on the order of 10^{-6} $M_\odot$ per year, consistent with the accretion rates inferred for very young low-mass stars.

Figure 1b shows images of this model at different rotational phases. Our results compare well with those of WW, in that we reproduce the shifts in the centroids of the bright and faint nebula and the change in contrast between the bright and faint nebula with rotational phase. The models generally match the most obvious features in the bright nebula, such as its brightening and fading and its strong asymmetry in our 1998 image. However, for the bright (upper) nebula these models do not produce a lateral asymmetry as prominent and extended as the one seen in the 1998 image. Conversely, the models predict a prominent, oppositely directed asymmetry in the faint (lower) counternebula which is not observed. The simplest model with bipolar accretion hot spots therefore requires some modification if it is to be reconciled with the variability seen in HH 30.

By allowing different brightnesses for the two hot spots, it becomes easier to match the observations. In Fig. 1c, we show simulations in which the lower hot spot is eliminated. A fainter lower spot appears to be required to match the 1998 image, when only a weak suggestion of an asymmetry is present in the lower nebula. How could the two hot spots, or their beaming efficiency, be so different between the two magnetic poles? Significant differences in the spot properties (such as their relative sizes, location with respect to the rotation axis, and incoming mass accretion rate) might be expected if the stellar magnetic field geometry were more complex than a simple dipole. It is tempting to speculate that the complex field geometry needed to break the hot spots' bipolar symmetry could also be the origin of the distinct properties of the HH 30 jet and counter jet. Future theoretical work on the magnetocentrifugal acceleration of Herbig-Haro jets should address how a complex stellar magnetic field might lead to jets and counter jets with different excitations, proper motions, and opening angles, as are observed for HH 30 (Ray et al. 1996).

Our results indicate that modified magnetic accretion models may be able to account for the variable asymmetries which we have discovered in HH 30. However, further progress now depends on obtaining additional data to to determine the degree to which the nebular variability is stochastic or periodic, to determine its spectral signatures, and to more firmly establish its characteristic timescale. T Tauri stars with accretion disks are known to have rotation periods on the order of 5-10 days (Edwards et al. 1993). If the magnetic accretion model is correct, the bright lateral asymmetry should flip from one side to another on a comparable timescale. Furthermore, hot spot illumination should cause the broadband colors of the lateral asymmetry to appear bluer than the rest of the nebula. The absence of these effects would lend support to the clumpy inner disk model. Although additional HST imaging will be very important to characterizing the physical mechanism responsible for the variability, groundbased monitoring of the brightness, polarization, and astrometric centroid of HH 30 can play important roles as well.

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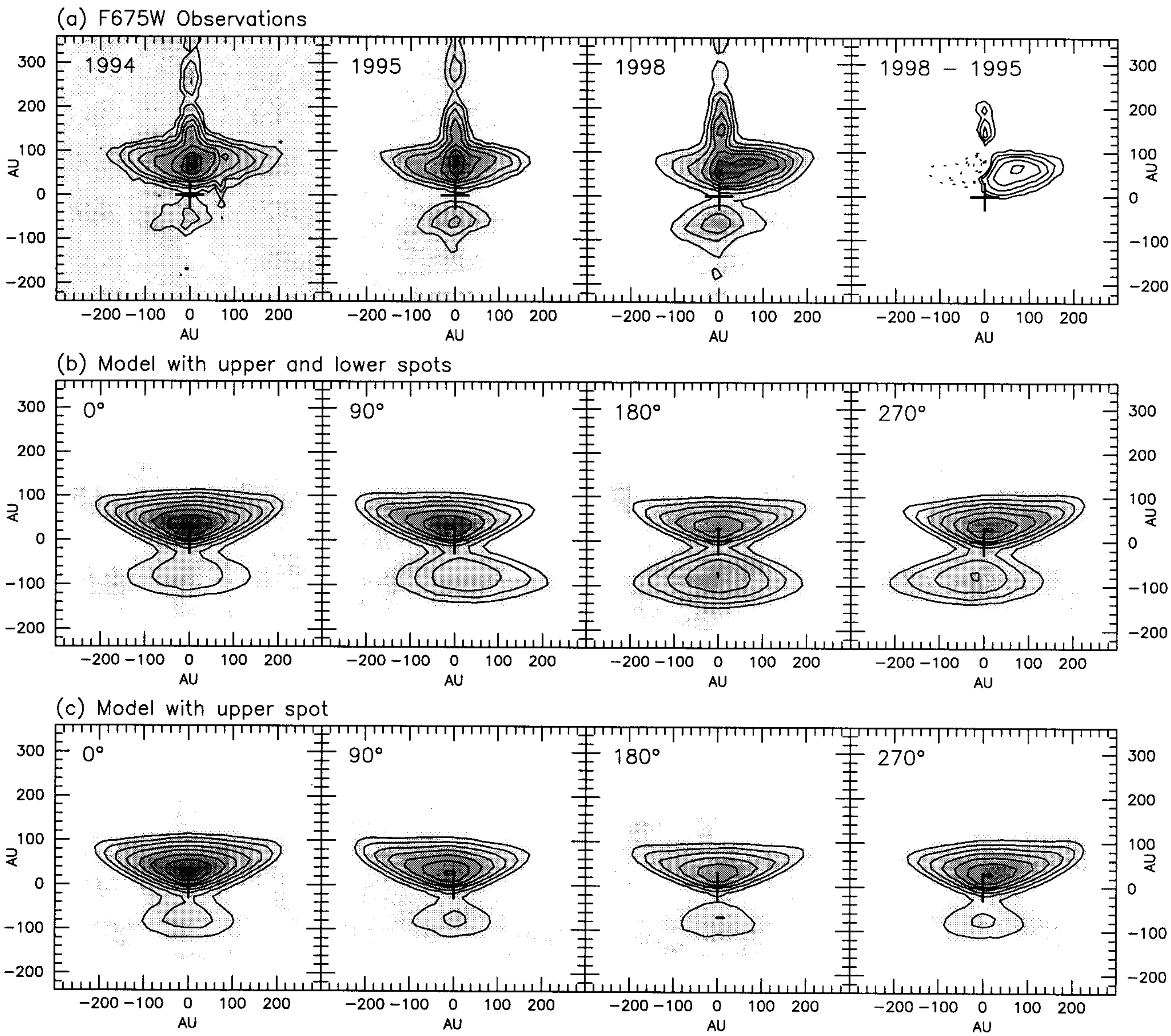
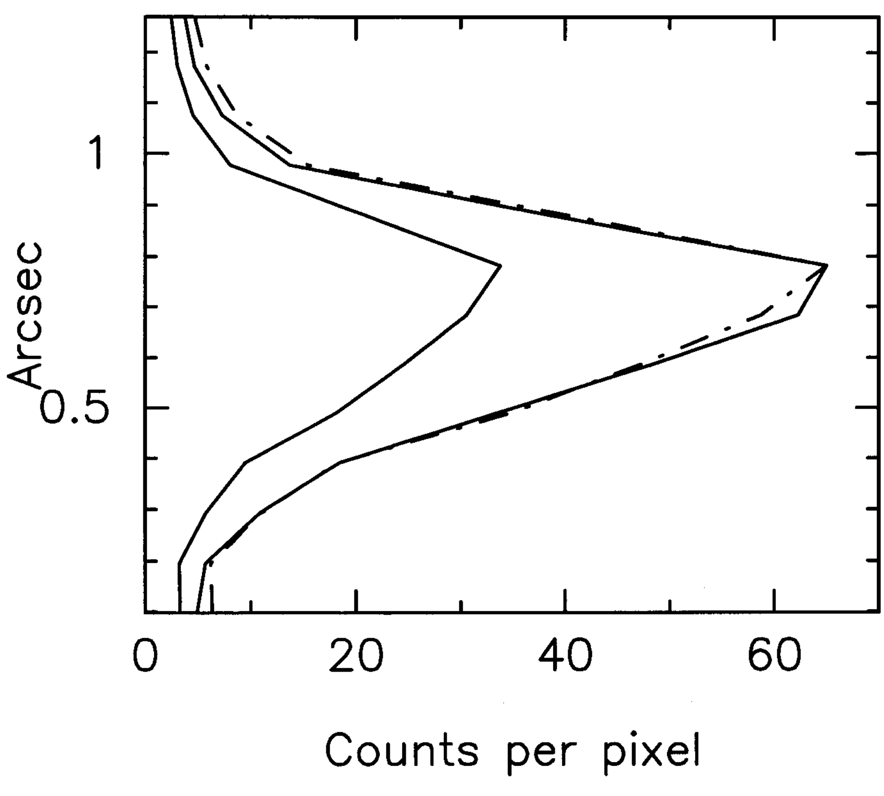
Fig. 1.— (a) Surface brightness maps of HH 30 in the F675W filter. The origin is the stellar position determined by Burrows et al. (1996), and the position angle of the bright jet (32°) is oriented vertically up each panel. The first three panels show images from the three epochs with contours spaced by 0.5 mag; the lowest contour level is 19.5 mag arcsec^{-2}. The fourth panel shows the difference between the 1998 and 1995 images, with positive (solid) and negative (dashed) contours with the same absolute values as in the first three panels. (b) Our multiple scattering model of a disk illuminated by a star with upper and lower hot spots; the model is detailed in the text. Four different rotational phases are shown; at 0°, the upper hot spot is tilted toward the observer. The contours are spaced by 0.5 mag. (c) As for (b), using the same absolute contour levels, except that the lower hot spot has been eliminated. The models have been convolved with an appropriate HST point spread function generated by the Tiny Tim program (Krist 1995).

Fig. 2.— Vertical brightness profiles of the HH 30 disk in 1995 (solid line, left) and 1998 (solid line, right). Cuts were made through the right side of the upper reflection nebula, perpendicular to the disk, at a projected distance of 7 pixels (100 AU) from the jet axis, and using a swath 3 pixels (40 AU) wide. The origin for the vertical axis is the center of the dark lane (i.e., the disk plane). The dashed line shows the 1995 data renormalized to the same peak brightness as 1998; its close match to the 1998 data shows that the vertical profile of the disk is unaffected by the variable asymmetry.



(a) F675W Observations
1994
1995
1998
1998 – 1995
(b) Model with upper and lower spots
0°
90°
180°
270°
(c) Model with upper spot
0°
90°
180°
270°
AU
300
200
100
0
−100
−200
−200 −100 0 100 200


1
Arcsec
0.5
0
20
40
60
Counts per pixel